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Paper

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# Closed loop identification using a modified Hansen scheme

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**Abstract.** It is often not feasible or even impossible to identify a plant in open loop. This might be because the plant contains unstable poles, or it is simply too expensive to remove the plant from its intended operation, among other possibilities. There are several methods for identifying a plant in closed loop [4], and one such method is the Hansen scheme [1]. Standard identification using Hansen scheme demands generating the identification signals indirectly. In this paper it is instead proposed to use the relationship between the Youla factorization of a plant and its stabilizing controller to directly measure the signals used for identification. A simulation example and identification of a gas bearing is given to show the method in action. Rotors supported by controllable gas bearings are open loop stable systems. However as the rotational speed is increased feedback control is necessary in order to keep the system stable. Furthermore because the dynamics of such a system depends on the rotational speed it is needed to conduct an identification while the system is part of a closed loop scheme. The authors believe the paper able to contribute towards a simpler and more direct way of identifying closed loop plants using Hansen scheme.

## 1. Introduction

Identification of closed loop systems is of great interest for many practical application. It is often not possible to conduct open loop identification on a plant. This can be due to several reasons, such as the system being open loop unstable, or disconnecting the controller being too costly. The Hansen scheme is a method for identification of closed loop systems, proposed by Fred Hansen [1]. The method takes advantage of the parametrization of all plants stabilized by a specific controller.

The experimental design procedure proposed by Fred Hansen demands the use of signals, which are not directly measurable from the plant  $G$ . It is therefore necessary to recreate the signals from known signals sent through predefined filters. The advantage of the method proposed in this paper is to get rid of the step of recreating the signals and instead measure directly the equivalent signals from the controller. Such a change will eliminate any need of a priori knowledge of the system states and reduce the amount of numerical inaccuracies related to the identification procedure.

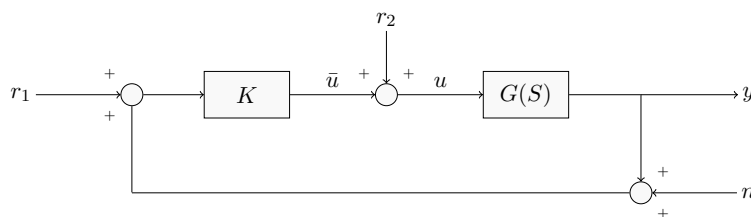


In this paper the control architecture is based on a Luenberger observer design. The identification method proposed will be shown theoretically as well as experimentally, using data from a rotor-bearing system linked to a controllable gas bearing. However the method can easily be used with other controller architectures.

The paper is structured as follows: Section 2 introduces Hansen scheme and how to conduct identification of closed loop systems; Section 3 introduces the coprime factorization of plant and controller together with a Youla parametrization; Section 4 presents results from a simulation example for the reader; Section 5 presents an identification example of a gas bearing; Section 6 contains a conclusion on the results presented in the paper.

## 2. Closed loop identification using the Hansen Scheme

The Hansen scheme is a method originally introduced by Fred Hansen [1] for identification of plants connected as part of a closed loop scheme. In this section a brief description of the Hansen scheme is given together with a motivation for modification. The method takes advantage of the coprime factorisation of plant and controller and is based on the theory outlined in [7]. A standard setup for a plant as part of a closed loop scheme can be seen in Fig. 1. Here the signals  $r_1$  and  $r_2$  can be both known or unknown disturbance input. Let  $G$  be the nominal plant and  $K$



**Figure 1.** Closed-loop system representation.

be the nominal controller, a coprime factorization of the nominal plant is then given in Eq. (1) and a coprime factorization of the nominal controller is given in Eq. (2), given the 8 matrices satisfies the double Bezout identity shown in Eq. (3).

$$G = NM^{-1} = \tilde{M}^{-1}\tilde{N} \quad (1)$$

$$K = UV^{-1} = \tilde{V}^{-1}\tilde{U} \quad (2)$$

$$\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} = \begin{bmatrix} \tilde{V} & -\tilde{U} \\ -\tilde{N} & \tilde{M} \end{bmatrix} \begin{bmatrix} M & U \\ N & V \end{bmatrix} = \begin{bmatrix} M & U \\ N & V \end{bmatrix} \begin{bmatrix} \tilde{V} & -\tilde{U} \\ -\tilde{N} & \tilde{M} \end{bmatrix} \in \mathbf{RH}_\infty \quad (3)$$

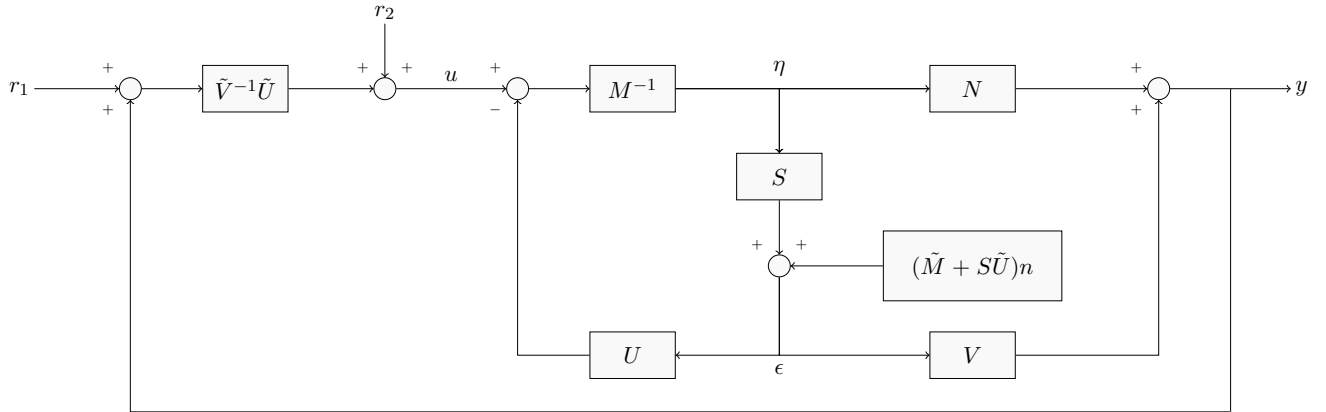
With a coprime factorization of the nominal plant  $G$  and of the controller  $K$  stabilizing the nominal plant  $G(0)$ , Eq. (4) gives a parametrization of all plants stabilized by the nominal controller  $K$  [3].

$$G(S) = (N + VS)(M + US)^{-1} = (\tilde{M} + S\tilde{U})^{-1}(\tilde{N} + S\tilde{V}) \quad (4)$$

The goal of the identification method is to find a signal uncorrelated with the output disturbance,  $n$ , to use for identification of the open loop error system, denoted  $S$  in Eq. (4).

The real plant can be described using the nominal controller and nominal plant together with the open loop error. Such a description is shown in Fig. 2 [1]. Here the output noise have been





**Figure 2.** Block representation of the Hansen Scheme.

moved to inside the plant. This representation is believed to make it easier to determine the impact of the noise on the identification process.

For the representation shown in Fig. 2 it is possible to recreate the signal  $\eta$  from the 2 input,  $r_1$  and  $r_2$  which are independent of the input and output noise. The calculation of  $\eta$  is given by Eq. (5) to Eq. (10).

$$u(t) = (M + US)\eta(t) + U(\tilde{M} + S\tilde{U})n(t) \quad (5)$$

$$y(t) = (N + VS)\eta(t) + V(\tilde{M} + S\tilde{U})n(t) \quad (6)$$

$$\tilde{V}u(t) - \tilde{V}(M + US)\eta(t) = \tilde{U}y(t) - \tilde{U}(N + VS)\eta(t) \quad (7)$$

$$\tilde{V}(\tilde{V}^{-1}U(r_1(t) + y(t)) + r_2(t)) - \tilde{V}(M + US)\eta(t) = \tilde{U}y(t) - \tilde{U}(N + VS)\eta(t) \quad (8)$$

$$\tilde{U}r_1(t) + \tilde{V}r_2(t) = \tilde{V}(M + US)\eta(t) - \tilde{U}(N + VS)\eta(t) \quad (9)$$

$$\eta(t) = \tilde{U}r_1(t) + \tilde{V}r_2(t) \quad (10)$$

In a similar fashion it is possible to calculate  $\epsilon$  using only the input measurements  $u$  and the output measurements  $y$ . How to calculate  $\epsilon$  is derived in Eq. (11) to Eq. (15).

$$M\eta(t) = u(t) - U\epsilon(t) \quad (11)$$

$$N\eta(t) = y(t) - V\epsilon(t) \quad (12)$$

$$\tilde{N}u(t) - \tilde{N}U = \tilde{M}y(t) - \tilde{M}V\epsilon(t) \quad (13)$$

$$\tilde{M}y(t) - \tilde{N}u(t) = (\tilde{M}V - \tilde{N}U)\epsilon(t) \quad (14)$$

$$\epsilon(t) = \tilde{M}y(t) - \tilde{N}u(t) \quad (15)$$

With the signals  $\eta$  and  $\epsilon$  it is possible to identify the open loop error system  $S$  as shown in Eq. (18), which is an open loop identification problem.

$$\eta(t) = \tilde{U}r_1(t) + \tilde{V}r_2(t) \quad (16)$$

$$\epsilon(t) = \tilde{M}y(t) + \tilde{N}u(t) \quad (17)$$

$$\epsilon(t) = S\eta(t) + d(t) \quad (18)$$

Because the signals  $\eta$  and  $\epsilon$  are internal signals in the plant it is impossible to measure them directly. It is therefore necessary to create them from the already known signals, as shown in Eq. (16) and Eq. (17). This approach might give lead to numerical problems because of how the signals are calculated, while the input signals are also led through a filter shaping the excitation signal. Furthermore initial conditions might increase the uncertainty of the signal estimation. It is therefore believed by the authors that it is a huge advantage to measure the signals directly instead.

The rest of the paper will outline a method for how to directly apply a signal equivalent to  $\eta$  and how to measure a signal equivalent to  $\epsilon$  using a full order observer based controller. A simulation example will be given and results from applying it to a gas bearing is finally presented.

### 3. Controller plant relationship

In this section the relationship between the parametrization of all controllers stabilised by a specific plant and all plants stabilized by a specific controller investigated. The results stated in the following section can also be found in [3] [8].

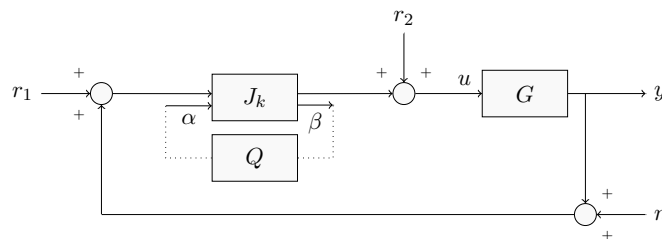
As shown in [3] [7] all controllers stabilising a specific plant is given in Eq. (19).

$$K(Q) = (U + MQ)(V + NQ)^{-1} = (\tilde{V} + Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M}) \mid Q \in \mathbf{RH}_\infty \quad (19)$$

$$K(Q) = \mathcal{F}_l(J_k, Q) \quad (20)$$

$$J_k = \begin{bmatrix} K & \tilde{V}^{-1} \\ V^{-1} & -V^{-1}N \end{bmatrix} \quad (21)$$

It is easy to see that the parametrization can be represented as a lower linear fractional transformation [5]. Such a controller can be implemented as seen in Fig. 3. Here  $Q$  is chosen to be zero, a set up which will be used throughout the rest of the paper. It is easy to see in Fig. 3 that by closing the loop from  $\beta$  to  $\alpha$  using  $Q$ , the controller is given as in Eq. (19).



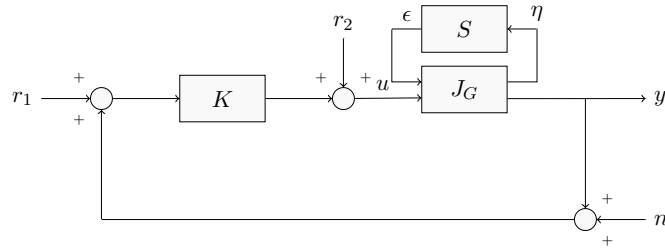
**Figure 3.** Closed loop description with a controller given as in Eq. (19), where the system  $Q$  is disconnected.

Equivalently it is possible to state all plants stabilised by a specific controller as shown in Eq. (22).

$$G(S) = (N + VS)(M + US)^{-1} = (\tilde{M} + S\tilde{U})^{-1}(\tilde{N} + S\tilde{V}) \mid S \in \mathbf{RH}_\infty \quad (22)$$

$$G(S) = \mathcal{F}_u(J_G, S) \quad (23)$$

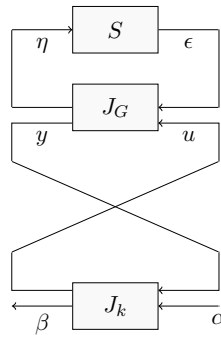
$$J_G = \begin{bmatrix} -M^{-1}U & M^{-1} \\ \tilde{M}^{-1} & G \end{bmatrix} \quad (24)$$



**Figure 4.** General lower LFT description of  $G(S)$ .

Again it is possible to represent  $G(S)$  as an upper LFT as shown in Fig. 4. It is important to notice that the signals  $\eta$  and  $\epsilon$  shown in Fig. 4 are the same  $\eta$  and  $\epsilon$  signals as shown in Fig. 2.

Combining  $J_k$  and  $J_G$  as shown in Fig. 5 it is possible to calculate the transfer function from each input to the two outputs.



**Figure 5.** Block representation of the relationship between  $G(S)$  and  $K(Q)$ .

It is easy to see that the cross coupling of  $J_k$  and  $J_G$  in Fig. 5 can be calculated as a redheffer star product. The gains of the block is shown in Eq. (25).

$$J_G \star J_k = \begin{bmatrix} \mathcal{F}_l(J_G, K) & M^{-1}(\mathbf{I} - KG)^{-1}\tilde{V}^{-1} \\ V^{-1}(\mathbf{I} - GK)^{-1}\tilde{M}^{-1} & \mathcal{F}_u(J_k, G) \end{bmatrix} \quad (25)$$

In order to determine the relationship between the signals on each side of the system  $Q$  and the system  $S$  the gains of the redheffer starproduct shown in Eq. (25) are calculated. First the transfer function from the output of  $S$  to the input of  $S$  is found:

$$\mathcal{F}_l(J_G, K) = -M^{-1}U + M^{-1}K(I - GK)^{-1}\tilde{M}^{-1} \quad (26)$$

$$= -M^{-1}U + M^{-1}UV^{-1}(I - GK)^{-1}\tilde{M}^{-1} \quad (27)$$

$$= -M^{-1}U + M^{-1}UV^{-1}(I - \tilde{M}^{-1}\tilde{N}UV^{-1})^{-1}\tilde{M}^{-1} \quad (28)$$

$$= -M^{-1}U + M^{-1}UV^{-1}V(\tilde{M}V - \tilde{N}U)^{-1}\tilde{M}\tilde{M}^{-1} \quad (29)$$

$$= -M^{-1}U + M^{-1}U(\tilde{M}V - \tilde{N}U)^{-1} \quad (30)$$

$$= -M^{-1}U + M^{-1}U(\mathbf{I})^{-1} \quad (31)$$

$$= 0 \quad (32)$$

The transfer function from the output of  $Q$  to the input of  $Q$  can in a similar fashion be proved to be 0. It is therefore only left to show the transfer function respectively from the output of  $Q$  to the input of  $S$ , which can be seen in Eq. (34) and from the output of  $S$  to the input of  $Q$ , which can be seen in Eq. (33).

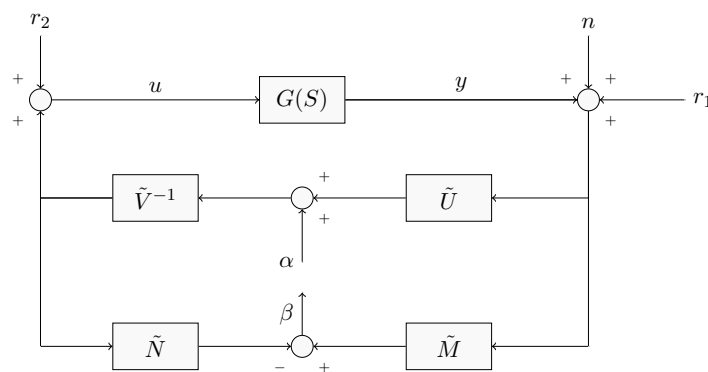
$$\begin{aligned} M^{-1}(\mathbf{I} - KG)^{-1}\tilde{V}^{-1} &= M^{-1}(\mathbf{I} - \tilde{V}^{-1}\tilde{U}NM^{-1})^{-1}\tilde{V}^{-1} \\ &= M^{-1}M(\tilde{V}M - \tilde{U}N)^{-1}\tilde{V}\tilde{V}^{-1} \\ &= (\tilde{V}M - \tilde{U}N)^{-1} = \mathbf{I} \end{aligned} \quad (33)$$

$$\begin{aligned} V^{-1}(\mathbf{I} - GK)^{-1}\tilde{M}^{-1} &= V^{-1}(\mathbf{I} - \tilde{M}^{-1}\tilde{N}UV^{-1})^{-1}\tilde{M}^{-1} \\ &= V^{-1}V(\tilde{M}V - \tilde{N}U)^{-1}\tilde{M}\tilde{M}^{-1} \\ &= (\tilde{M}V - \tilde{N}U)^{-1} = \mathbf{I} \end{aligned} \quad (34)$$

Combining the results from Eq. (32),(33) and (34) the relationship between  $\alpha$  and  $\beta$  can be described as in Eq. (35). The result can be found in [3] where the relationship between  $Q$  and  $S$ , to the best of the authors knowledge, was examined for the first time.

$$\beta = S\alpha \quad (35)$$

It is thus proved that the input signal of  $S$  is equal to the output signal of  $Q$  and the output signal of  $S$  is equal to the input signal of  $Q$ . It is therefore possible to directly measure the signals equivalent to  $\eta$  and  $\epsilon$  from the parametrized controller as the signals  $\alpha$  and  $\beta$  respectively. To the best knowledge of the authors this approach is not limited to a specific controller architecture, but can be applied to any controller implemented as showed in Fig. 6.



**Figure 6.** General controller scheme using a coprime plant and controller description.

The approach demands that it is possible to find the signals  $\alpha$  and  $\beta$  in the controller. This is in this paper done using an observer based controller. It is important to notice the order of the recast controller is increased by twice the order of the nominal plant model. It can therefore be convenient to use an observer based control scheme, where the order of the controller is 2 times the order of the nominal plant, which is the minimal order possible for such a controller set up.

For a controller given as in Fig. 6 as part of a closed loop as shown in Fig. 1 the closed loop transfer functions are given in Eq. (36), where  $\alpha$  is a free signal to choose for identification purposes.

$$\begin{bmatrix} y \\ u \\ \beta \end{bmatrix} = \begin{bmatrix} (N + VS)\tilde{U} & (N + VS)\tilde{U} & (N + VS)\tilde{V} & N + VS \\ (M + US)\tilde{U} & (M + US)\tilde{U} & (M + US)\tilde{V} & M + US \\ \tilde{M} + S\tilde{U} & \tilde{M} + S\tilde{U} & \tilde{N} + S\tilde{V} & S \end{bmatrix} \begin{bmatrix} n \\ r_1 \\ r_2 \\ \alpha \end{bmatrix} \quad (36)$$

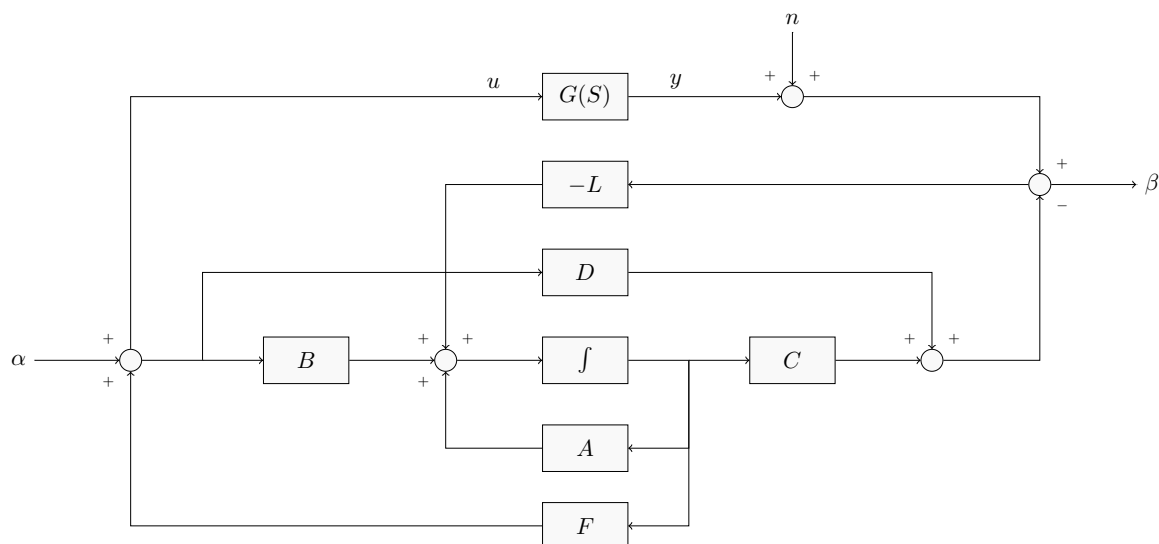
By applying a known disturbance signal on both the observer input and the plant input, hence the  $\alpha$  signal, it is possible to measure  $\beta$  as the difference between the predicted output by the observer and the output from the plant  $G(S)$ . This method is seen as superior in regards to the freedom of the identification signal compared to the method proposed in [1], where the excitation signal is imposed through  $r_1$  and  $r_2$ . It is clear from Eq. (36) that the 3 excitation signals and the disturbance signal are uncorrelated why open loop identification can be conducted.

#### 4. Simulation example

A simulation example is presented to give the reader some insight into the identification procedure. A random open loop stable plant with 2 inputs, 2 outputs and 4 states is generated. The nominal plant is chosen such that the system matrix ( $A_{model}$ ) is 70% of the actual system matrix ( $A_{real}$ ) as shown in Eq. (37).

$$A_{model} = 0.7 \cdot A_{real} \quad (37)$$

The nominal plant have thus both an dynamic and steady state error that needs to be identified. The test set up is shown in Fig. 7 where both the unknown disturbance signal,  $n$ , and the excitation signal ( $\alpha$ ) are implemented as white noise signals. The amplitude of the noise was chosen to be 10% of the  $\beta$  signal. Furthermore only output noise,  $r_1$ , was used for this simulation.



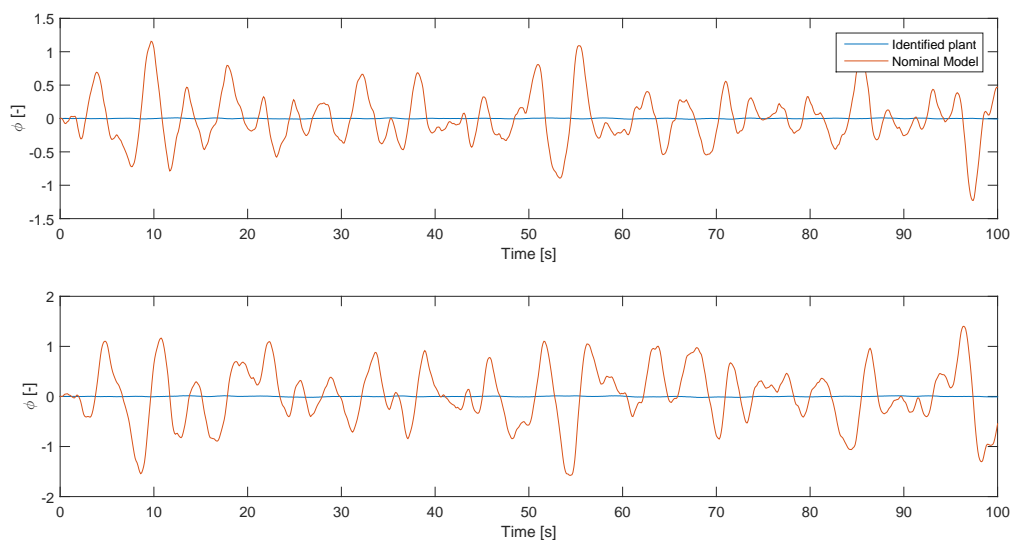
**Figure 7.** Block diagram of simulation example. The observer is designed for a plant where the elements of the system matrix is only 70 % of the actual values of the elements of the system matrix. The state feedback is designed using LQR design and the observer poles are placed to have insignificant dynamics compared to the state feedback poles.

The order of the state space model is chosen by calculating the real open loop error, which was found to be a 12'th order system. It is therefore possible to identify the real open loop error,  $S$ , as a 12'th order system, why the open loop error is identified as a 12'th order state space model.

In order to be able to determine the goodness of a model an error signal is calculated using Eq. (38).

$$\phi(t) = G_{real}u(t) - G_{model}u(t) \quad (38)$$

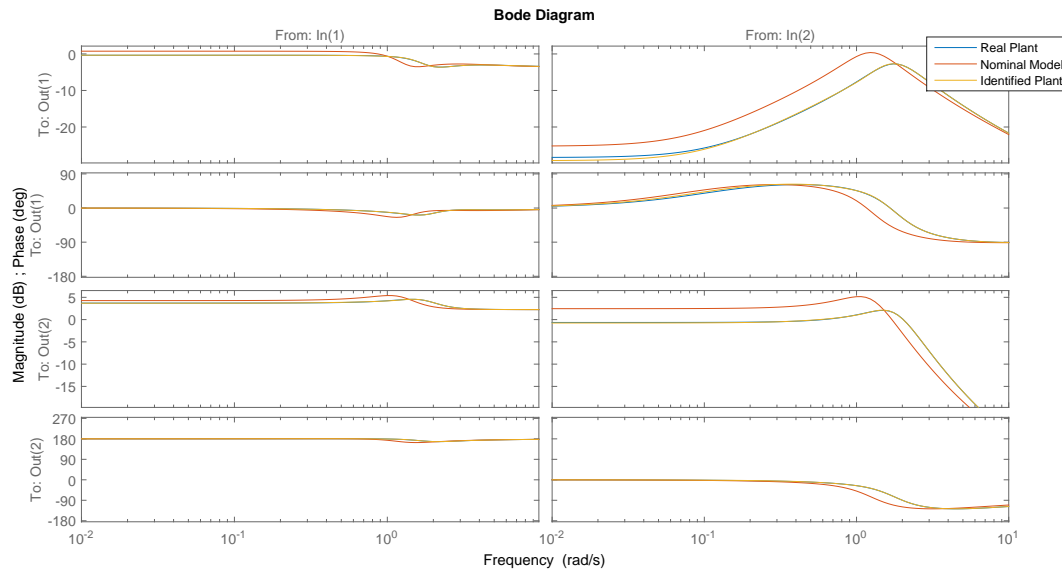
An error signal sequence of respectively the nominal model and the identified plant, using Eq (38), can be seen in Fig. 8. It is clearly seen that the identified plant reduce the output error why it can be concluded possible to improve the nominal model, which was on purpose designed to be imperfect. The dynamics are identified although there is still a small deviation between the identified and the real plant, which is due to numerical issues and presence of output noise on the identification signal. It is important to note that there is not applied any noise to the validation data shown in Fig. 8 why any deviation from zero corresponds to a deviation between the real plant and respectively the nominal or identified plant.



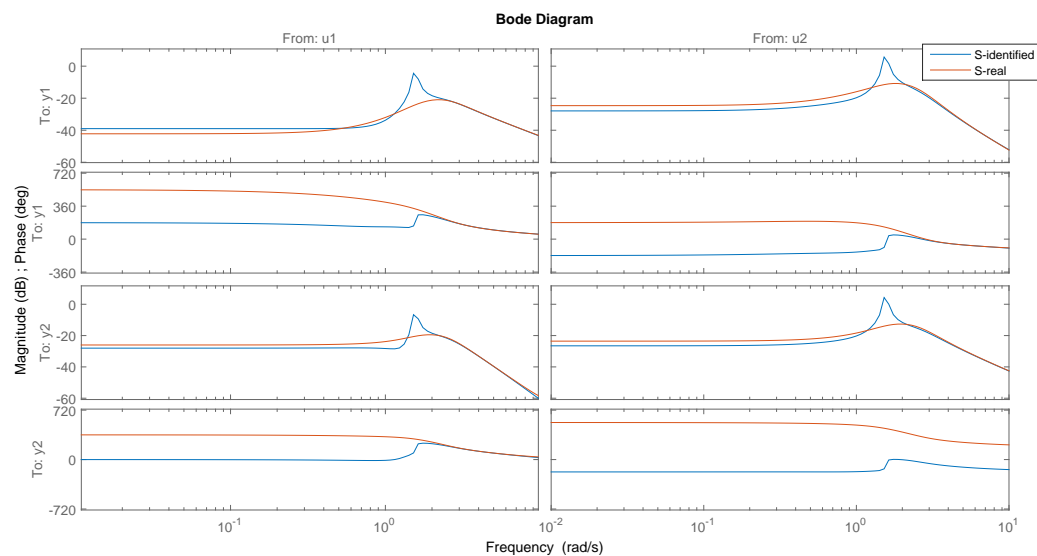
**Figure 8.** Goodness of fit of Nominal and identified plant. Each signal is calculated using Eq. (38). The top plot shows respectively nominal and identified model for the first output, while the lower plot shows the signal for output 2. The identified plant have a better goodness fit which can be seen from the variance in the signal being lower than for the nominal model while the mean is at 0.

A bode plot of respectively the real plant, the identified plant and the plant model is shown in Fig. 9. It is easily seen from the bode plot that the model does not agree with the real plant. However the identified plant have successfully minimized the error over the whole frequency span.

For validation of the identification procedure it is also possible to compare the real  $S$  with the one identified through the identification procedure. A bode plot of the identified and real  $S$  are shown in Fig. 10.



**Figure 9.** Bode plot of the real plant, the identified plant and the plant model. The plant model and real plant are clearly not the same, while the identified plant have almost same frequency response as the real plant.

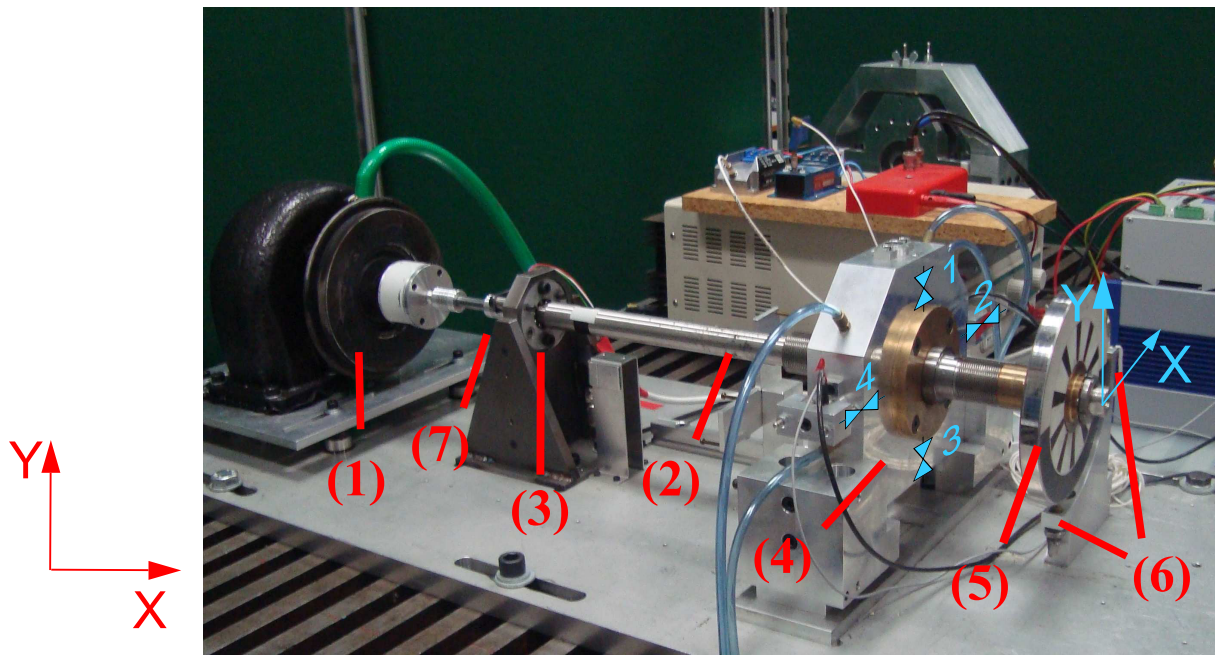


**Figure 10.** Bode plot of the real  $S$  calculated as described in [3] and the identified  $S$  using the procedure described in section 3.

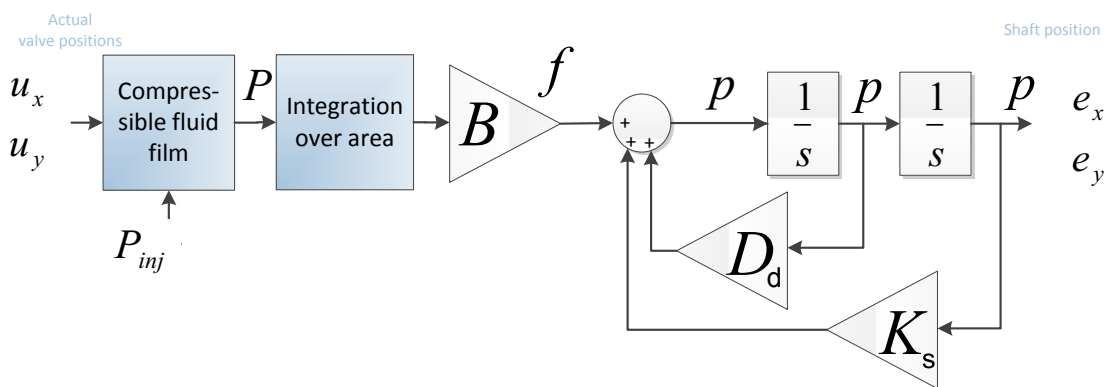
## 5. Lab experiment

Identification of a gas bearing test rig is given to show the identification procedure with data obtained from a real system. A photo of the gas bearing test rig is shown in Fig. 11.

A block diagram of the test rig is shown in Fig. 12. Here  $\mathbf{K}_s$  describes the direct stiffness and cross stiffness of the gas bearing,  $\mathbf{D}_d$  the direct damping and cross damping of the gas bearing and  $\mathbf{B}$  is the direct input gain and cross input gain of the gas bearing.



**Figure 11.** Photo of the gas bearing test rig. Here (1) is the turbine, (2) is the flexible shaft, (3) is a ball bearing, (4) is the gas bearing, (5) is a disc used for preload the journal and (6) is the displacement sensors.



**Figure 12.** Block diagram representation of the gas bearing test rig.

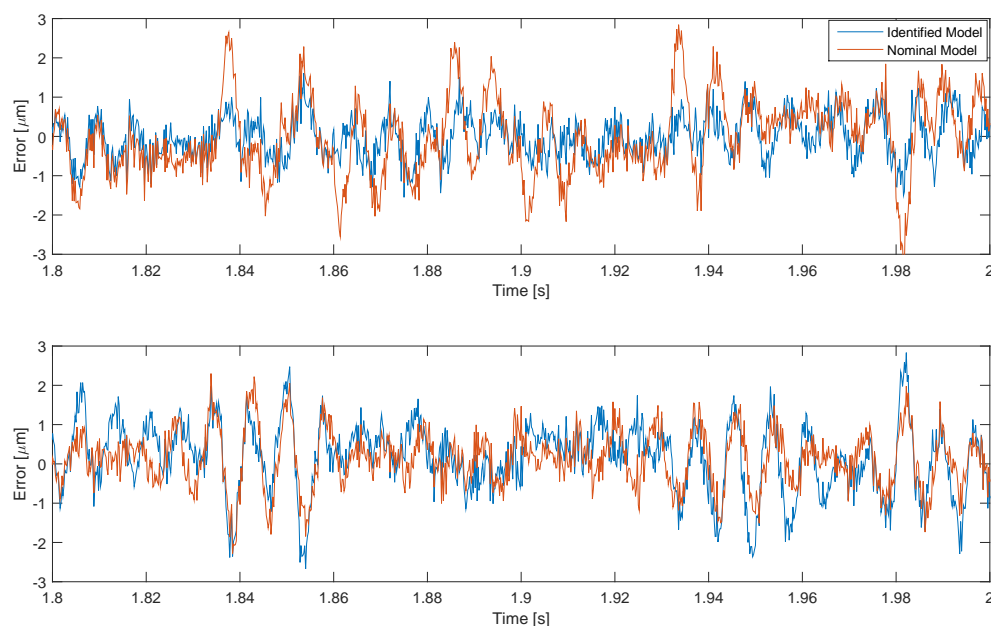
The rotor-bearing system thus consists of 8 states, 2 inputs and 2 outputs. A model for this set up have been derived and identified in [9] where the gas bearing is not a part of a closed loop Scheme. The identification shown in this section is based on non-rotating shaft levitated by the externally presented gas bearing shown in Fig. 11, as part of a closed loop scheme. The controller implemented is designed as a standard Luenberger observer where the observer gain and state feedback gain is chosen using lqr design. It is important to note that the gas bearing is open loop stable at zero rotational speed. It is therefore possible to identify the plant using open loop techniques. However the point is to show that the method is applicable why it will be possible to use the same method for higher rotational speeds. At higher rotational speed the



rotor-bearing is open loop unstable why only closed loop identification will be possible.

For identification an observer with state feedback is designed and as for the simulation example showed in section 4 a white noise excitation signal is applied as the  $\eta$  signal in the horizontal and vertical direction. The open loop error,  $S$ , is estimated as a 8'th order system, same order as the nominal model, which is found to produce a good identification result.

An error plot as described in Eq. (38) is presented in Fig. 13 using both the nominal model and the identified model. For validation the excitation signal is only applied in the horizontal direction. It is worth noticing that the nominal model is a good representation of the test rig, why the error is relative small compared to the output noise which is measured to have an amplitude of  $1 \mu\text{m}$ .



**Figure 13.** Plot of the error between the predicted output and measured output for horizontal and vertical direction. The top plot shows the error in the horizontal direction, while the bottom plot shows the error in the vertical direction.

From Fig. 13 it can be seen that the identification have produced a more accurate model for prediction of the horizontal direction (the top plot), while there is no significant improvement in the vertical direction. The error in the horizontal direction is reduced to close to  $1 \mu\text{m}$  which is the level of the output noise induced by the displacement sensors. The result suggests that it has been possible to identify the direct gains from horizontal input to horizontal output while the cross coupling between the two inputs have not been improved through the identification. It is believed possible to identify the direct gain in the vertical direction with a pure vertical excitation signal in a likewise manner.

## 6. Conclusion

Identification using Hansen scheme has so far been conducted using indirect excitation signals for identification. Such an approach makes it difficult to determine the frequency response of the excitation signal. In this paper a method is given, on how to use the equivalent signals in the controller, for identification of the open loop error system  $S$ , thus letting the excitation be

imposed without pre filtering which is the case with the original method proposed in [1]. It is therefore believed that the Hansen scheme is a more limiting special case of the identification approach outlined in this paper. The paper outline an approach for how to excite a plant and measure the needed signals for identification, given an observer based controller. The paper furthermore shows how it is possible to recast any controller such that it is possible to excite and measure the signals used here for identification. Using a simulation example and a Gas Bearing system for identification the method is proven to work.

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